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Earthquake-controlling Processes of Detachment Zones in Eastern North China

SUN Aiqun[1], NIU Shuyin[1], SHAO Ji'an[2], HOU Quanlin[3] and ZHANG Jianzhen[1]
1 *Shijiazhuang College of Economics, Shijiazhuang, Hebei 050031; E-mail: niusy@sjzue.edu.cn*
2 *School of Earth and Space Sciences, Peking University, Beijing 100871*
3 *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100101*

Abstract The basin-and-range area in eastern North China is known for frequent occurrence of earthquakes, their great magnitudes and heavy losses thereby incurred. Seismic studies in the past usually emphasized the intersections, inflexions and branches of the faults. However, the intensities of many great earthquakes in this area do not show linear distribution, and the epicenters are horizontally dispersed at certain depths instead of along the strike of faults. Based on the sub-mantle plume studies made by authors in the past decade, it is thought that there exists an uplifted sub-mantle plume under the fault depression area in North China. The uplifting and intrusion of mantle materials caused the upper crust to be faulted, while low-velocity and high-velocity layers are alternatively distributed in the middle crust under the influence of the mantle and the lower crust. The middle and lower crust materials were detached from the top of the sub-mantle plume to the surroundings while the sub-mantle plume materials were detached outward. When the detached middle and lower crust come to the boundary of fault basins in the upper crust, they will be obstructed by the orogenic zone and the detachment will go slower. The shearing between them will cause the stress to accumulate and release alternatively, so that earthquakes occurred frequently in the areas of sub-mantle plume and its surroundings.

Key words: sub-mantle plume, detachment belt, earthquake-controlling structure, low-velocity and high-conductivity zones, north China basin-and range area

1 Introduction

Earthquakes greatly threaten and imperil the human society and economic development. Because the epicenter is usually within the lithosphere, studying the relationship between its processes of "gestation", occurrence and development and the deep structures is one of difficult problems in modern earth sciences. Much exploration is required for this work (Teng, 2001).

Based on the sub-mantle plume studies we have made in the past decade in eastern North China, the earthquakes in this area are not only controlled by deep faults, but constrained by declined detachment belts in the deep crust, and especially, they are controlled by the detachment zone related to the North China sub-mantle plume.

More than 90% of earthquakes in the world are structural earthquakes. North China is an earthquake-frequent area; many intensive earthquakes happened in eastern North China since the Xingtai earthquake in 1960s, causing great losses of life and property, which has aroused the attention of the governments and seismologists. Geologists, seismologists and geophysicists have made deep researches on the focal mechanism, epicenter parameters and earthquake intensity; they have even measured the vector displacement of earthearthquake-triggering structures. Therefore, we can say that the seismic study and earthquake prediction in China are on the advanced list of the world (Seismological Bureau of China, 1982; Ma, 1982; Liu et al., 1986; Song et al., 1993; Wang et al., 1994).

With the progress of geoscientific studies, it is indicated that the gently declined detachment zones in the crust are the dominant structures for most earthquakes. This theory may provide a new approach for studying the mechanism and prediction of earthquakes.

2 Distribution of Earthquakes

In the lithosphere, there exist not only fractures of different directions, magnitudes and depths, but also layered structures such as the upper, middle, lower crust and the asthenosphere, as well as gentle declined detachment zones which started or ended at these layers. The seismic studies in the past usually lay emphasis on the intersections, branches, inflexions and end points of steep faults, and it is considered that stress is easily concentrated in these places. When the stress accumulates to the critical point, an earthquake can be triggered by occasion. There are indeed this type of earthquake-triggering structures, the study of which is significant to seismic geology and earthquake prediction.

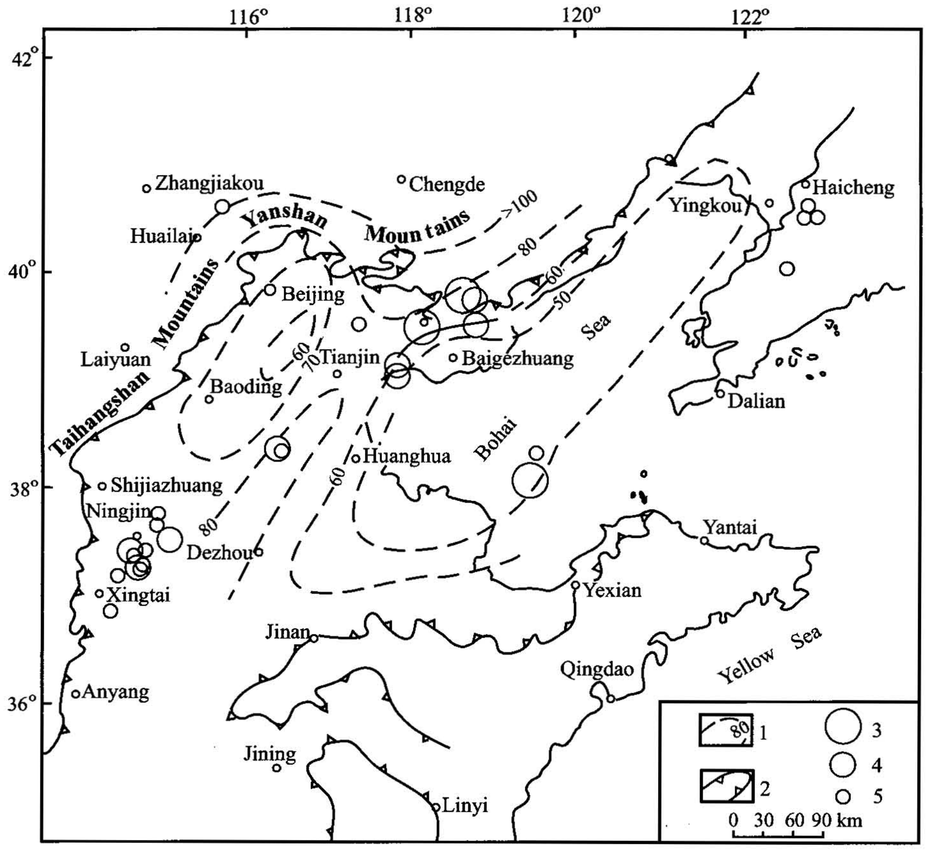

Fig. 1. The relationship between the upper mantle high-conductivity layer uplift and earthquakes in the basin-range area of North China.

1. Isobath of the upper mantle high-conductivity layer; 2. boundary between basin and range; 3. M_s=7.9–7.0; 4. M_s=6.9–6.0; 5. M_s=5.9–5.0.

Recently, the study of multistage evolution of the mantle plume and the tectonic geology of the sub-mantle plume enlighten geologists to understand earthquakes from the view point of layered structure and detachment zone, which provides a new approach for studying the mechanism and prediction of earthquakes.

2.1 Regional distribution of earthquakes

Earthquake is an energy-releasing phenomenon in the crust. Earthquakes occurring at different times may show a definite regional distribution, based on which seismologists or geologists can study their distribution, earthquake-triggering structures and make mid-term and long-term predictions.

Within the ten years between the Xingtai earthquake and the Tangshan earthquake, there occurred 32 earthquakes with magnitudes over 5 in eastern North China, of which five are of magnitudes 7–7.9, ten of magnitudes 6–6.9 and seventeen of magnitudes 5–5.9. Their distribution range is mainly limited the North China fault depression area or its surroundings (Fig. 1), especially characterized by surrounding the mantle-uplifting area, and the epicenters are mainly in the shallow part of lithosphere, at depths of tens of kilometers (Ma et al., 1982).

The seismic intensities of the Xingtai, Bohai, Haicheng and Tangshan earthquakes show an isoaxial distribution (Fig. 2). This character may indicate that the earthquake-triggering structures may not occur along the strike of an exposed steep fault, but are distributed along a detachment belt at a definite depth of the lithosphere. Whether a normal fault or an inverse fault, the displacement of a detached fault always moves along a gently declined detachment zone, so that the epicenters are distributed at a limited depth, or the contour lines of intensities are nearly isoaxial.

2.2 The profile distribution of earthquakes

The depth of an epicenter is an important parameter in the measurement of basic seismic parameters. Although the accuracy of the measurement is related to such factors as the distribution of seismic stations and the regional crustal structure and the measurement may have errors, depth is still significant for the study of earthquake sequences.

From the Tangshan earthquake on July 28, 1976 (M_s=7.9) to the end of 1979, there were about 34%

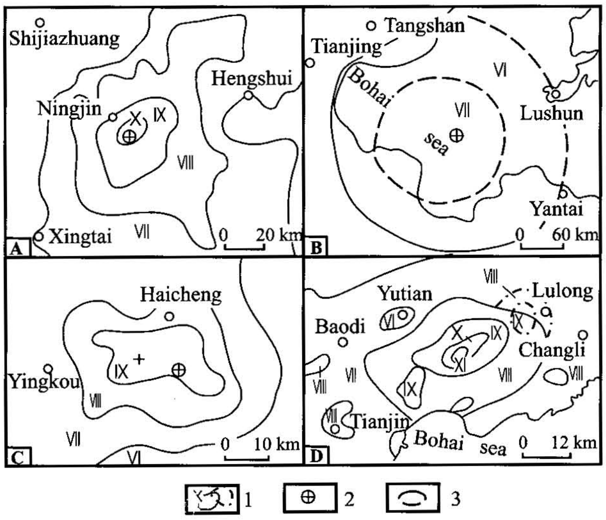

Fig. 2. Distribution of earthquake intensities (modified from Ma et al., 1982).

A. Xingtai earthquake; B. Bohai earthquake; C. Haicheng earthquake; D. Tangshan earthquake

1. Counter lines of earthquakes and intensity; 2. localities of epicenters; 3. reference counter lines of earthquakes.

earthquakes the depth of which can be measured in the total earthquake sequence (including the aftershocks). Statistics indicate that 91.7% of the earthquakes have focal depths < 20 km, 7.2% with focal depths of 20–29 km, and only about 1.1% occurring at depths ≥30 km, averaging at 11.5 km. The depth of the Tangshan earthquake (M_s=7.9) is close to that in Luanxian County (M_s=7.1), both above the average depth of their aftershocks. Three important aftershocks (over 6 in magnitude) also have the same depth; averaging at 18 km (Seismological Bureau of China, 1982). After the Tangshan great earthquake, the Seismological Bureau of China made many artificial earthquakes in Beijing, Tianjin and Tangshan, and interpreted the results (Sun, 1989). According to the statistics of measured focal depths in the Beijing-Tianjin-Tangshan areas (M_s≥3.0) before 1980, the depth of epicenters is well correlated with the structure of the lithosphere (Fig. 3). Based on the North China earthquake records (M_s≥3.0) from the International Seismic Data Center (1966–1998) and earthquake records (M_s≥2.0) from the Center of National Digital Seismic Station Net (1978–2001), Zhou and He (2003) made a statistics of focal depths of shallow earthquakes in North China. The results show that earthquakes with focal depths about 10 km have the highest frequency of occurrence, and those occurring in the middle-lower crust are obviously less frequent than those in the middle-upper crust (Fig. 4). There is another peak value at the depth of 33 km, i.e. there exists a dense earthquake layer at the bottom of the crust. The epicenters of the Xingtai earthquake in 1966 are also distributed in a horizontal layer, the average depth of which is 23 km (Fig. 5).

Earthquakes in other areas of Hebei Province have similar characters (Hebei Seismological Bureau, 1986). Based on the analysis of velocity distribution and tectonic layering in the crust and mantle, most earthquake epicenters are distributed in the detachment zone between the (brittle) upper crust and the (low-velocity and high-

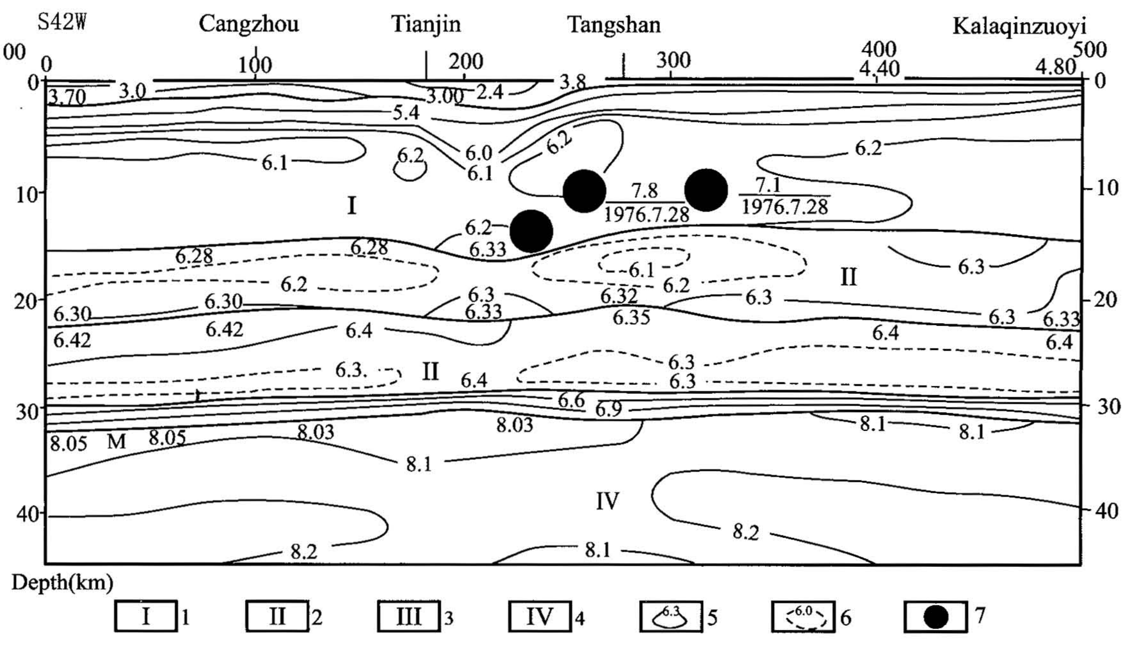

Fig. 3. Crust-mantle velocity and earthquake-controlling structures in Tangshan (after Sun et al., 1989).

1. Upper crust; 2. middle crust; 3. lower crust; 4. upper mantle; 5. isoseismal line of seismic wave velocity; 6. intracrustal low-velocity layer; 7. seismic epicenter.

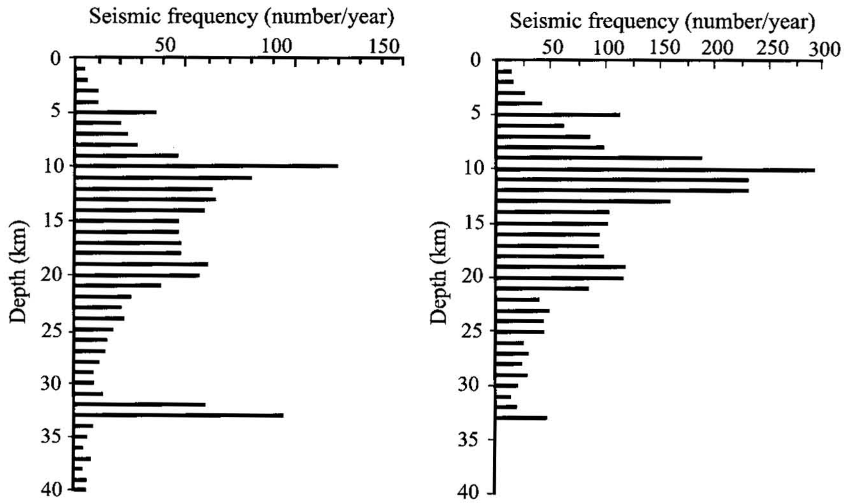

Fig. 4. Distribution of epicenters in North China (after Zhou and He, 2003).

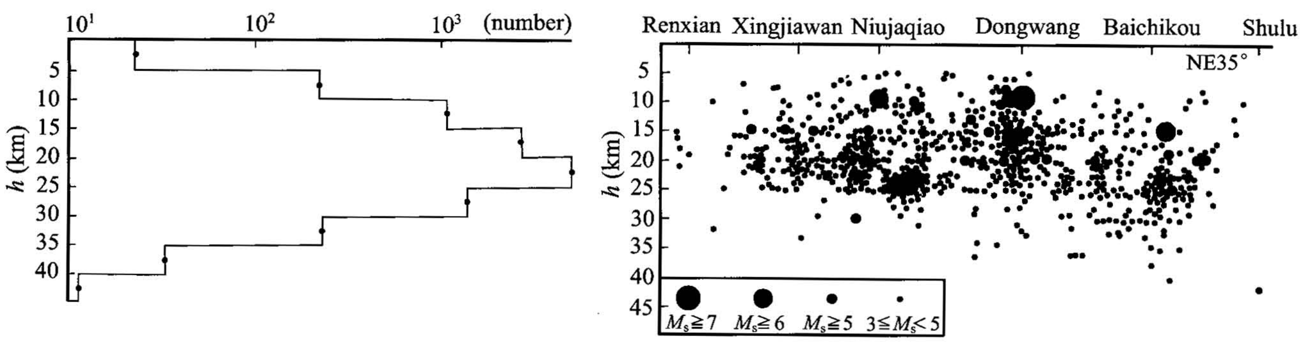

Fig. 5. Distribution of epicenters in the Renxian-Shulu profile (Hebei Seismological Bureau, 1986).

conductivity) middle crust, or the alternative velocity zones in the middle crust (Fig. 4).

The above data and the profile features of earthquake epicenters indicate that earthquakes are not obviously distributed along a steep fault, but tend to spread along a detachment zone at certain depths. Similarly, the epicenters may also be distributed along a gentle declined detachment belt.

2.3 Discussion on earthquake-controlling structures

If earthquake-controlling structures are not only a group of steep faults, but are more often distributed along a gently declined detachment zone, we should pay more attention to the layered structures of the lithosphere, especially those detachment zones which started or ended at these layers. It is indicated that the lithosphere is obviously layered, and different places have different layers. Taking the North China basin-and-range area as an example, the uplifting of mantle is prominent in this area, the crust is thinned and active, so that earthquakes are frequent and with large magnitudes. Away from this area the crust is thickened, the activation is weakened and the magnitude and intensity of earthquakes are lowered.

Geophysical prospecting indicates that the upper crust in eastern North China is dominated by sedimentary layers, the thickness of which in the center of the basin is about 10 km. They can be divided into three velocity layers: the Ceno-Mesozoic cover, the Paleozoic cover and the crystallized basement. The middle crust is mainly a low-velocity layer, which shows an alternative distribution of high- and low-velocity layers; the minimum velocity is 5.8–6.0 km/s. The thickness in the central basin is only 8–10 km and up to 12–20 km near the mountainous area. The lower crust is a positive velocity gradient layer; the velocity is 6.2–6.4 km/s in the top and 7.3–7.6 km/s at the bottom. It is also thickened toward the surrounding mountains and its velocity near the boundary of the crust and mantle is obviously increased. The thickness of this transition layer varies from 2 km in the basin's center to 5–6 km in the peripheries, and the velocity leaps from 7.3–7.6 km/s to 8.0–8.1 km/s (Sun, 1989). The velocity layers of the lithosphere are clearly shown in the seismic CT profile. In addition, there develop many listric faults within the crust, which are gradually merged to the middle crust at a small declined angle. For example, the decoupling fault between the Taihang Mountains and the North China faulted basin has been considered a great deep fault based on the interpretation of the Taihangshang gravity gradient. Recent studies indicate that it is actually a normal listric fault. It tends to be gently declined at the depth of 17 km and gradually convergent to the crust. This is a detachment belt which is developed in the upper crust (Liu et al., 2003). Sun reported (2003, unpublished) that there exists a huge detachment structure system in the central Hebei depression, which is extended in the west and reversed in the east, involved more than 150 km in width. Qi and Yang (2003) found that there is a huge detachment belt dipping southeast in the southern Huanghua basin.

Intensive earthquakes in North China, such as in Xingtai, Bohai, Haicheng and Tangshan, all occurred around the uplifted sub-mantle plume in the center of the basin with complicated crust structure. Their epicenters are mostly within the high-conductivity layers or on the top of the low-velocity layers. These special layers seem to be the bottom boundary of seismic activities, which indicates that the stress accumulation is mainly in the low-velocity or above the high-conductivity layers in the crust. These features may be related to the characteristics of the low-velocity and high-conductivity layers, as well as the evolution of crust-mantle in this area (Niu et al., 1996, 2001). Based on the exploration of deep structure in the Xingtai and Tangshan earthquake areas, Liu Guodong (1983) proposed that the epicenters of intensive earthquakes mainly lie in the footwall of shallow listric faults and between the break points of concealed steep faults in the crust. These places usually are the intersections of detachment belts and concealed steep faults. Intensive earthquakes usually take place in brittle crust above low-velocity and High-conductivity layers. The mantle is partially uplifted and mantle material filtered into the crust in the epicenter distribution area. From a CT tomography analysis, Liu et al. (1986) and Sun et al. (1993) reported that continental earthquakes mainly take place in transition zones between low-velocity and high-conductivity layers, and closer to the latter. Based on a study of 3-D velocity structure in intensive earthquake areas, Mei (1997) considered that (1) the crust in the intensive earthquake areas is usually characterized by a multi-layered structure with alternative distribution of high-velocity and low-velocity layers, and the high-velocity layers are usually consistent with the earthquake layers; (2) the velocity of the upper mantle is relatively low beneath the intensive earthquake areas, corresponding to the uplift of the upper mantle; (3) the epicenters of intensive earthquakes do not correspond fully with the deep faults. Wang et al. (1994) indicated that detachment structures are common in the North China basin based on a study of seismic reflection sections.

We can conclude, from the above descriptions, that intensive earthquakes are closely related to the uplift of the mantle, and the detachment structures seem to be the dominant earthquake-controlling or earthquake-triggering structures.

3 Earthquake-controlling Mechanism of the Sub-mantle Plume

The North China area has undergone the stages of the formation (Ar-Pt_1) and stable development (Pt_2-Pz) of the paleo-continent, and entered the intensively active period since the Yanshanian movement (Mz-Kz), and is characterized by the multistage evolution of the mantle plume. In the North China basin-and-range area, large-scale fault basins were formed, which were controlled by a series of listric faults; in some secondary faulted basins Cenozoic sediments alone were accumulated up to 5000–9000 m in thickness. The average accumulation of modern sedimentation rate still keeps at 1–3 mm/a (Wang, 1995). Surrounding mountains, such as the Yanshan Mountains, Taihang Mountains, the Shandong-Liaoning mountainous area and the Dabie Mountains were intensively uplifted by 10–20 km, forming a typical basin-and-range structure. The shape of the mantle is mirrored with the fault-depression and surrounding mountains in North China. In the North China fault-depression area, the upper mantle is intensively uplifted, and the lithosphere is obviously thinned. This evolution is actually a specific representation of the multistage evolution of the mantle plume.

Our understanding of the mantle plume can be traced back to the hotspot theory. In 1963 and 1973, Wilson used the hotspot theory to interpret the formation of the Hawaiian island volcano chains. Morgan (1972) considered that the fixed mantle hot source proposed by Wilson is actually the mantle plume occurring near the thermal boundary at the bottom of the mantle. Deffeys (1972) considered that the mantle plume was formed through the upwelling of the lower mantle. Anderson (1975) suggested that the mantle plume should be defined chemically instead of physically. Its chemical composition is obviously different from that of the surroundings. It originated from the D″ layer at the bottom of the mantle. The D″ layer had concentrated a large amount of radioactive elements from the outer core. The radioactivity resulted in high temperature and low viscidity in the D″ layer, so that the mantle plume was formed.

The formation and evolution of the mantle plume are influenced by various factors; they have different evolution processes and shapes. On the basis of the seismic CT

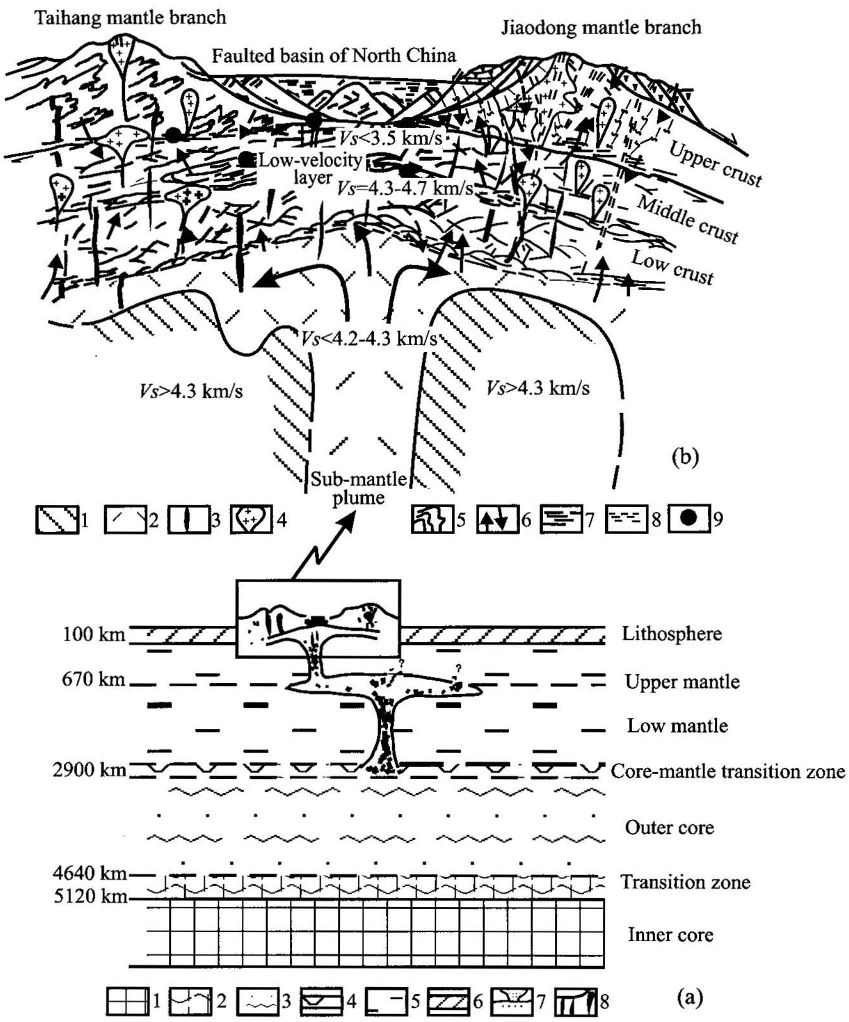

Fig. 6. Earthquake-controlling model of the mantle plume.
(a) Earthquake-controlling model of the mantle plume: 1. inner core; 2. transition zone between inner and outer cores; 3. outer core; 4. transition zone between core and mantle; 5. mantle; 6. lithosphere; 7. mantle plume–sub-mantle plume; 8. mantle branch. (b) Earthquake-controlling model of the sub-mantle: 1. brittle lithosphere; 2. sub-mantle plume; 3. basaltic dike; 4. granitic intrusion; 5. metamorphic rock series; 6. deep derived hydrothermal fluid and shallow atmosphere precipitation water; 7. low-velocity and high-conductivity layer; 8. ductile shearing belt; 9. earthquake-prone zone.

tomography, superhigh pressure experiment, computer modeling, and plate tectonics and comparative planet studies, Japanese geologists have enriched and embodied the theory of the mantle plume (Fukao et al., 1994; Maruyama et al., 1994). They studied the deep structure with the P-wave tomography technique, and took the depths of the core-mantle (2900 km), the bottom of the upper mantle (670 km) and the bottom of the lithosphere (100 km) as boundaries to divide the mantle plume into the primary, secondary and third plumes. They considered that the mantle plume has two originating depths: one is the boundary of the core and mantle (the D″ layer), the other is the depth <400 km. The mantle plumes originating from the D″ layer can further be divided into two types: super plumes with a diameter of about 5000 km and small plumes diameters <500 km. A super plume is shaped as a neck in the lower part of the lower mantle, and begins to spread out toward the bottom of the upper mantle (670 km) at the depth of about 2000 km, forming an oblate crown. It continues to evolve into several small (secondary) plumes when entering the upper mantle, named by Deng et al. (1992) as the "sub-mantle plumes". At the bottom of the lithosphere (100 km), they further evolve into smaller (third-order) plumes, which are named "mantle branch structures" by Niu et al. (1996). Super mantle plumes can have different appearances at the surface, such as uplifts, basins, mountain chains or sea ridges.

Although there are controversies about the formation, characteristics, size and uplifting speed of the mantle plumes, it is doubtless and objective to conclude that they originate from upwelling of deep materials within the earth.

Based on studies of the mantle plumes made by worldwide scholars, and a comparison with the geological evolution and tectonics in eastern North China, it is concluded that the basin-and-range area in eastern North China is a typical sub-mantle plume. A large volume of geophysical exploration data indicate that the basin-and-range area corresponds to the intensive mantle uplift beneath, and the uplifted materials are detached toward the surroundings in a mushroom shape. At the top of a sub-mantle plume, light mantle materials moved up poured out as basic dykes or basalts. This caused the upper crust to be heated and faulted, forming large faulted basins controlled by a series of listric faults, which received Cenozoic sediments about 10,000 m in thickness. The lithosphere is only about 60–80 km thick. In the surroundings of the North China sub-mantle plume, mantle materials spread outward in a hemispheric crown, and the lithosphere is speedily thickened to 100–120 km, especially toward the west and north. In the Taihang and Yanshan mountains areas, the lithosphere is 120–160 km thick, forming obvious mantle ridges or steps. Geologically, they are usually represented by thickness-break zones, gravity gradient zones, earthquake zones and hot-spring zones.

The velocity distribution of the lithosphere is clearly shown on a seismic CT profile. Let us take two CT profiles in the North China sub-mantle plume as example (one is along 36°N in E-W, the other is along 115°E in S-N): The sub-mantle plume in the North China basin-and-range area shows a clear uplifted hemispheric crown, whose top has risen to 50–70 km. At the depth of 30–50 km, there is a thin low-velocity layer inserting into the Taihang Mountains westward and the Shandong-Liaoning Mountains eastward on the 36°N profile. At the same depth, there is a thin low-velocity layer which inserts into the Yanshan Mountains on the profile of 115°E and cuts off the lithosphere. The velocity is only 6.1–7.6 km/s, which shows some melted character (Sun and Xing, 1994). In the Dabie Mountains, the low-velocity layer is uplifted to the depth of 30–50 km, which may be related to the speedy uplifting of the Dabie Mountains.

It is the mushroom-like spreading of the sub-mantle plume and the potential difference of the mantle that make the deep lithosphere materials to be rheomorphically detached toward the bottom of the orogentic belt via the crust-mantle transition zone and middle crust low-velocity zone (ductile rheomorphic belt). Because of the uplift of the asthenosphere and the swarming of mantle materials into the crust, the rise of the crust temperature results in enhanced plasticity of the lower crust (not melted). The middle and lower crust will then be easy to detach rheomorphically from the uplifted plume to the surroundings, which causes the crust to get thinned on the top of the sub-mantle plume and thickened around the plume. Moreover, the uplift of the sub-mantle plume not only causes the crust to be thinned, but the middle and lower crust on the top of the plume to be detached outward. If the crustal high-conductivity layers are in a partial melting state, they will become rheomorphic layers, and their outward detachment will be more prominent and will cause a displacement against the overlying brittle upper crust. In this case, the stress between the layers will accumulate continuously and release periodically. Therefore, the top and surroundings of a sub-mantle plume, especially the detachment zone between the middle crust rheomorphic layer and he upper crust brittle layer, are easy to develop and trigger earthquakes (Fig. 6).

4 Conclusion

Since the Mesozoic, the eastern part of North China has come into an active period, which is characterized by the multistage evolution of the mantle plume. There developed a typical sub-mantle plume underneath the North China faulted basin. The surface was then extended and faulted. The intrusion of upper mantle materials (basaltic lavas or dykes) heated the crust. Detachment took place in the lower crust and high-conductivity layers appeared in the middle crust. Driven by mantle materials and the detachment, lateral rheomorphism was developed in the high-conductivity layers. The overlying upper crust was obstructed when it was detached to the orogentic belt, and then shearing along the detachment belt resulted in stress accumulation and periodic release. This will induce earthquakes, even devastating earthquakes. The epicenters are distributed as isoaxial on the surface and irregular at a definite depth (such as the middle crust or the boundary between the middle crust and upper crust) on the profile.

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